

Symbol Error Rate Performance Evaluation of the LM37 Multimegabit Telemetry Modulator-Demodulator Unit

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The LM37 multimegabit telemetry modulator-demodulator unit was tested for evaluation of its symbol error rate (SER) performance. Using an automated test setup, the SER tests were carried out at various symbol rates and signal-to-noise ratios (SNR), ranging from +10 to -10 dB. With the aid of a specially designed error detector and a stabilized signal and noise summation unit, measurement of the SER at low SNR was possible. The results of the tests have shown that at symbol rates below 20 megasymbols per second (MS/s) and input SNR above -6 dB, the SER performance of the modem is within the specified 0.65 to 1.5 dB of the theoretical error curve. At symbol rates above 20 MS/s, the specification is met at SNR's down to -2 dB. This report presents the results of the SER tests with the description of the test setup and the measurement procedure.

I. Introduction

The current telemetry data handling capability of the Deep Space Network (DSN) is limited to 250 kilosymbols per second (kS/s). Ground telemetry systems for future planetary missions, such as Venus Orbiting Imaging Radar (VOIR) and Mars Rover, require the capability of processing much higher symbol rates than can presently be handled in the DSN.

The Multimegabit Telemetry Development (MTD) project was created for the purpose of developing the needed megasymbol telemetry technology. The developed technology will be used to upgrade and expand the telemetry data handling capability of the DSN. To accomplish the MTD project objectives, a developmental program leading to a feasibility model of a multimegabit telemetry demodulator-detector was initiated

at JPL. The program also included acquisition of a commercially developed multimegabit modem for test and evaluation in support of a make or buy decision. To fulfill the latter objective of the developmental program, the Linkabit LM37 multimegabit telemetry modulator-demodulator (MTMD) unit was purchased. This report presents the SER test and evaluation process of the commercial modem. Following are the descriptions of the modem, the test setup, the measurement procedure, the test results, and evaluation of the results with some concluding remarks.

II. LM37 MTMD Unit

The LM37 MTMD unit is a full duplex, digital biphasic, shift-keyed modem (Ref. 1). The unit has the capability of

modulating and demodulating a suppressed carrier at an intermediate frequency (IF) of 55 MHz with data rates ranging from 0.5 to 30 MS/s. Figure 1 shows the block diagram of the modem.

A. Modulator

The modulator portion of the modem has been provided for the purpose of testing the demodulator. The modulator accepts the telemetry (TX) data and the associated TX clock at a differential emitter coupled logic (ECL) level. The falling edge of the TX clock enters the TX data into a flipflop whose output biphase modulates the 55-MHz carrier signal. The carrier signal is generated by a phase-locked loop whose reference frequency is an external 5-MHz source. To eliminate carrier harmonics, the biphase modulated signal is first passed through a four-pole Butterworth bandpass filter, with a bandwidth of 60 MHz, centered at the carrier frequency of 55 MHz. The bandpass signal is then amplified to a zero dBm output level.

B. Demodulator

The demodulator portion of the LM37 MTMD unit produces four-bit (soft decision) data, labeled as RX data, and the corresponding symbol clock at a differential ECL level. The front end of the demodulator is an analog quadrature demodulator whose outputs are the lowpassed in-phase (I) and quadrature (Q) baseband signals. The I and Q channels are digitized into four bits of data, at a rate between 32 and 64 MS/s, depending on the input symbol rate. The digitized I and Q data are then used in all the subsequent digitally implemented functions. These functions include carrier acquisition and tracking, symbol acquisition and tracking, symbol and carrier lock detection, automatic gain control (AGC), and data detection.

The demodulator symbol rates, ranging from 0.5 to 30 MS/s, are entered through eight thumbwheel switches on the front panel. The front panel also contains the bit (symbol) and the carrier lock indicator lights. All of the input/output (I/O) signal connectors are located at the rear panel.

III. Automated Test Setup

Figure 2 shows the block diagram of the automated test setup which was used in the SER test of the LM37 MTMD unit. By configuring test instrumentation and support hardware around the HP-9845C desk top computer, accurate signal measurement and rapid data logging were possible. This test setup also provided a capability for on-line computation and verification of the test parameters. The functions of the various instruments in the test setup are given in the test procedure section. The following is a description of the special support hardware developed for the SER tests.

A. Noise Generator

The required white noise for the SER tests was generated by the noise generator of Fig. 3. The operation of the unit is based on amplification of the thermal noise contributed by the 50-ohm input terminating resistor and the equivalent input impedance of the preamplifiers. The bandwidth of the noise at the output of the preamplifiers extends from 5 to 500 MHz. Mixing the noise with a local oscillator (LO) accomplishes two objectives. First, the noise is translated closer to dc, and second, by selecting an appropriate LO frequency, noise folding can be used to improve noise spectrum flatness.

To exclude the higher frequency components of the mixed signal, it is passed through a five-pole Butterworth lowpass filter with 150-MHz bandwidth. The lowpass signal is then amplified and becomes the output noise signal with a uniformly distributed power spectrum in the desired frequency range. The regulation of the generated noise was measured to be ± 0.2 dB. Figure 4 shows the plot of the power density spectrum of the generated noise signal.

B. Stabilized Signal and Noise Summation Unit

The output power level of the noise generator is a function of the system noise temperature. By simply adding the generated noise to the signal, the resulting SNR level will vary as the system temperature varies with time. Such a variation in the input SNR will greatly affect the accuracy of the SER tests since the symbol errors are time averaged.

The stabilized signal and noise summation unit, shown in Fig. 5, was designed to maintain the input SNR at constant levels throughout the SER measurements. The SNR stability is achieved through a feedback control loop. Equal portions of signal and noise are compared by the null detector of Fig. 6. The result of the comparison (output of the null detector) is the control signal which is applied to the AGC circuit. The AGC circuit (see Ref. 2) changes gain in response to the above control signal, thus maintaining a constant SNR. The regulation of the feedback control loop was measured to be within ± 0.1 dB for ± 5 -dB changes in the signal or the noise power levels.

C. Interface Unit

An interface unit was designed to provide the required digital I/O signal levels for the LM37 MTMD unit. Figure 7 shows the schematic of the interface unit. The unit consists of an input and an output translator for the modulator input and the demodulator output. The input section translates the TX data and clock signals from a TTL level into a differential ECL level. The output section converts the symbol data and clock output of the demodulator from a differential ECL level into a TTL level. For the TTL-level translation, the

receivers and drivers are designed for 50-ohm coaxial cables. The receivers and drivers for the ECL-level translators are designed for 120-ohm triaxial cables.

D. Delay and Error Detector Unit

The delay and error detector unit of Fig. 8 was designed to detect symbol errors at very low SNR levels. Through a shift register, the data from the word generator (TX data) is delayed by a time delay equal to the internal delay of the LM37 MTMD unit. The delay time is set by a thumbwheel switch located on the front panel of the unit. A delay resolution of one-half symbol is required to permit clocking with the LM37 clock. To obtain this resolution, the TX data is shifted at twice the frequency of the TX clock. The shifting clock is divided by 2 and output as the TX clock.

The error detector section compares the delayed TX data with the detected RX symbol data from the demodulator. An error pulse is output when the RX symbol does not agree with the delayed TX symbol. To insure proper timing and also allow sufficient data settling time, the delayed TX data and the RX data are both sampled and stored for comparison at the trailing edge of the RX symbol clock from the demodulator. The two samples are then compared by means of an exclusive OR gate. The return-to-zero (RZ) symbol error pulse is obtained by gating the output of the exclusive OR gate with the delayed RX clock.

Because of the Costas carrier tracking loop in the demodulator, there is a 180° ambiguity in the polarity of the demodulated symbols. When the RX data is in the true or noninverted state, the detected symbol error pulses correspond to the actual symbol errors. However, when the RX data is in the complemented form, the detected symbol errors are also complemented. This ambiguity in the RZ symbol error pulse is resolved in the following way: For binary symbol data, the maximum possible error probability is 0.5. In terms of the SER, the maximum error probability corresponds to one-half of the input symbol rate. When the rate of the detected symbol errors is less than or equal to the above maximum rate, the resulting error pulses correspond to the actual SER. When the rate of the detected errors exceeds the maximum possible rate, the actual SER is obtained by subtracting the detected symbol error rate from the input symbol rate.

IV. Test Procedure

The SER testing of the LM37 MTMD unit was carried out in two phases. In the initial phase, the power measuring instruments, such as the HP-8568A spectrum analyzer and the HP-436A power meter, were calibrated with a known reference signal. Then the calibrated power meter was used to

determine power correction factors for the various symbol rates.

The second phase of the test consisted of a sequence of signal and noise power level settings, followed by the measurement of the input SNR and the corresponding SER. The sequence was repeated for each symbol rate. Each step in a sequence was executed according to directives issued by an HP-9845C computer control and monitor program. The detailed description of a typical sequence is given in Appendix A. Following is the description of the measurement methods and the technical aspects of the test procedure. The description makes reference to a more detailed block diagram (Fig. 9) of the test setup.

A. Calibration

The premeasurement calibration steps were carried out to insure the accuracy of the measured input SNR. To reduce the effect of the absolute accuracy of the test instruments, both the signal and the noise power levels were measured with the same instrument, namely, the HP-8968A spectrum analyzer.

The absolute accuracy of the measured power, displayed by the maximum value of the marker on the spectrum analyzer, is a function of several parameters. These parameters include uncertainty of the calibration and the reference level, the real fidelity between the reference level and the marker position, and the bandwidth accuracy of the selected filter (see Ref. 3). To eliminate the uncertainty in the calibration, the spectrum analyzer and the power meter were calibrated with the same known reference signal. For maximum accuracy, the coupled functions on the spectrum analyzer were selected such that the power readings on both instruments differed by less than 0.01 dB. The uncertainty in the reference level was removed by measuring the signal and the noise power levels using the reference levels on the spectrum analyzer which were calibrated with the power meter. By maintaining a 1-dB per division scale resolution on the spectrum analyzer, the scale fidelity error was reduced to within 0.01 dB.

B. Power Correction Factors

The power correction factors at different symbol rates are the ratios of the modulated signal power to the signal power with the modulation removed, as measured with the HP-436A power meter. Table 1 gives the value of the power correction factor as a function of the modulation symbol rate. These factors are required because of the effect of the output bandpass filter of the modulator. At low symbol rates, the difference in the power levels between the unmodulated signal and the modulated signal is small, since most harmonics of the modulated signal are present in the modulator output. The power difference becomes larger as the symbol rate increases, since

more harmonics of the modulated signal fall outside the bandwidth of the output filter.

C. Signal and Noise Power Measurement

For the evaluation of the input SNR, the power levels in the noise and the signal channels were separately measured with the HP-8568A spectrum analyzer. As shown in Fig. 9, the power measurement at the coupled port of the directional coupler 3 measures the same power ratios as appear at the input to the demodulator. The signal or the noise channel measurements were selected by the proper positions of the SW1 and SW2 switches. The SW3 switch was in the power meter position only during the calibration and the computation of the power correction factors.

In the SER curves, the input SNR level is expressed in terms of the ratio of the energy per symbol (ST_s) to the noise power spectral density (N_0). N_0 can be directly measured with the spectrum analyzer in units of dB/Hz in the selected bandwidth. For greater accuracy the value of N_0 was obtained from the average of 100 points, measured in a 25-85 MHz bandwidth. The selected bandwidth was equal to the bandwidth of the input filter in the LM37 demodulator.

It is difficult to directly and accurately measure the total modulated signal power from its power spectrum, especially when the carrier is modulated with pseudorandom (PN) data. For this reason, the modulated signal power level was determined by first measuring the unmodulated carrier signal power with the spectrum analyzer. This was done by removing the PN data (through the SW4 switch) from the modulator input. The total modulated signal power was then obtained by correcting the measured carrier power with the corresponding power correction factors. The following expression was used to compute ST_s ,

$$ST_s = (P_c \cdot F_{ps})/S$$

where P_c is the carrier power, and F_{ps} is the power correction factor at symbol rate S .

D. Symbol Error Rate Measurement

SER was measured by counting the symbol error pulses with the HP-5370A counter. To reduce the variance of the sampled error pulses, a time average of 100 seconds was used. The value of SER was determined by the ratio of the averaged symbol error pulses to the modulation rate (symbol rate).

E. Control and Monitor Program

Under the supervision of a software program, written in BASIC, the HP-9845C computer controlled and monitored

the flow of data to and from the test instruments. The interfacing of the test instruments was accomplished with the HP-IB (IEEE 488) interface card. The control program monitored the test process and issued commands to the instruments. The program also displayed the directives for the manual functions, such as keyboard entry of the test parameters. The measured data were manipulated and stored for off-line graphic display of the test results.

V. Test Results

The results of the SER tests for the various symbol rates are summarized in two types of graph. These graphs, consisting of the SER and the input SNR degradation curves, were prepared with the HP-9845C computer and the HP-9872B plotter. The following are the descriptions of the two types of graph.

A. SER Curves

The SER curves present the relations between the LM37 demodulator input SNRs and its output probability of symbol errors (P_e) at the various symbol rates. These curves were generated by plotting the logarithm of SER versus the ST_s/N_0 , expressed in units of dB. For comparison, the theoretical error probability curve is plotted along with each of the SER curves. Figure 10 corresponds to the results of the SER tests at extreme and midrange symbol rates.

For the plotting of the theoretical error curve, the error probability for a given SNR was computed from the following expression,

$$P_e = \frac{1}{2} \operatorname{erfc}(\sqrt{ST_s/N_0}) = \frac{1}{2} [1 - \operatorname{erf}(\sqrt{ST_s/N_0})]$$

The erf function was evaluated by using the following approximation,

$$\operatorname{erf}(x) = 1 - (a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5) e^{-x^2} + \epsilon(x),$$

where $t = 1/(1 + P)$, $|\epsilon(x)| < 7.5 \times 10^{-8}$, p and a_i , $i = 1, 2, \dots, 5$ are known coefficients (see Ref. 4).

B. Input SNR Degradation Curves

The input SNR degradation curves represent a quantitative measure of the demodulator SER performance. Figure 11 shows the input SNR degradation curves for 11 different symbol rates.

The input SNR degradation curves were generated from the SER curves by first determining for each measured value of SER (P_e) the corresponding SNR values from the measured and the theoretical SER curves. The difference between the two SNR values constituted the degraded input SNR. These different values were then plotted versus the SNR values obtained from the measured SER curves. The SNR values from the theoretical curves were determined by evaluating the following rational approximation of the inverse erfc function

$$ST_s/N_0 = [\operatorname{erfc}^{-1}(2P_e)]^2$$

$$\operatorname{erfc}^{-1}(2P_e) = \frac{1}{\sqrt{2}} \left[t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} + \epsilon_Q \right]$$

where $t = \sqrt{\ln 1/(P_e^2)}$, $|\epsilon_Q| < 4.5 \times 10^{-4}$, and the c and d coefficients are known constants (see Ref. 4).

VI. Conclusions and Remarks

The SER performance of the LM37 modulator unit for symbol rates ranging from 0.5 to 20 MS/s and input SNR above 6 dB is within the specified 0.65 to 1.5 dB of the theoretical error probability curve. At symbol rates higher than 20 MS/s, however, the SER specification is not met for input SNRs lower than -2.0 dB. Because of loss of the carrier lock, SER testing at input SNR lower than -6 dB was not possible. Table 3 shows the LM37 modulator SER specifications at $ST_s/N_0 = -4$ dB against the measured values.

The effect of the change in bandwidth of the demodulator input filter on SER performance is observed at some selected symbol rates. For example, contrary to what is expected, the input SNR degradation at 8.0 MS/s is 0.2 dB lower than at 7.99 MS/s. This difference in the SER performance is due to a change of the input filter to a wider bandwidth at 8.0 MS/s than at 7.99 MS/s.

The automated test setup will be used to further test and evaluate the LM37 MTMD unit. The followup testing will include acquisition time and phase jitter measurements. The test setup will also be used to evaluate the feasibility model of the multimegabit modulator-detector system which is being developed at JPL.

References

1. *Technical Manual For Megasympol Telemetry Modulator-Demodulator*, Linkabit Corp, Part No. 21340, May 1980.
2. Stevens, G. L., "Input Signal Conditioner for the Multimegasympol Telemetry System Feasibility Model," *TDA Progress Report 42-58*, May-June 1980, pp. 49-58, Jet Propulsion Laboratory, Pasadena, Calif., August 15, 1980.
3. *Operating and Service Manual for 8568A Spectrum Analyzer*, Volume 1, Hewlett Packard Part No. 08568-90012, October 1978.
4. Abramowitz and Stegun, *Handbook of Mathematical Functions*, National Bureau of Standards, 1968.

Table 1. Power correction factor

Symbol rate, MS/s	Correction factor, dB
0.50	-0.060
1.00	-0.060
3.99	-0.060
4.00	-0.06
7.99	-0.07
8.00	-0.07
15.99	-0.14
16.00	-0.14
20.00	-0.18
29.99	-0.26
30.00	-0.26

Table 2. LM37 internal delay time and required setting on the delay and error detector unit

Symbol rate, MS/s	Internal delay		Delay switch setting
	Time, nsec	Symbols	
0.50	8300	4.15	0-1
1.00	4260	4.26	0-1
3.99	1227	4.89	2-3
4.00	1265	5.06	2-3
7.99	714	5.70	3-4
8.00	763	6.10	4-5
15.99	463	7.40	6-7
16.00	509	8.14	8-9
20.00	438	8.76	10
29.99	352	10.50	12-13
30.00	350	10.50	12-13

Table 3. LM37 SER performance specifications vs measured values at $ST_S/N_0 = -4$ dB

Symbol rate, MS/s	SER deviation from theoretical		Performance margin, dB
	Specification, dB	Measured, dB	
0.50	0.65	0.76	-0.11
1.00	0.65	0.69	-0.04
3.99	0.65	0.50	+0.15
4.00	0.65	0.55	+0.10
7.99	0.65	0.71	-0.06
8.00	0.65	0.51	+0.14
15.99	1.00	0.97	+0.03
16.00	1.00	1.00	0.00
20.00	1.00	1.01	-0.01
29.99	1.50	2.55	-1.05
30.00	1.50	2.44	-0.94

Appendix A

Measurement Procedure

The following is a typical sequence of steps which were carried out in the second phase of the test procedure:

1. Set the LM37 unit at the test symbol rate.
2. Set the HP 3225A frequency synthesizer at twice the test symbol rate.
3. Select the delay time corresponding to the test symbol rate (see Table 2).
4. Set SNR approximately to 10 dB.
5. Press the RUN key on the HP 9845C computer keyboard. From this point on the measurement procedures followed the control and monitor program directives.

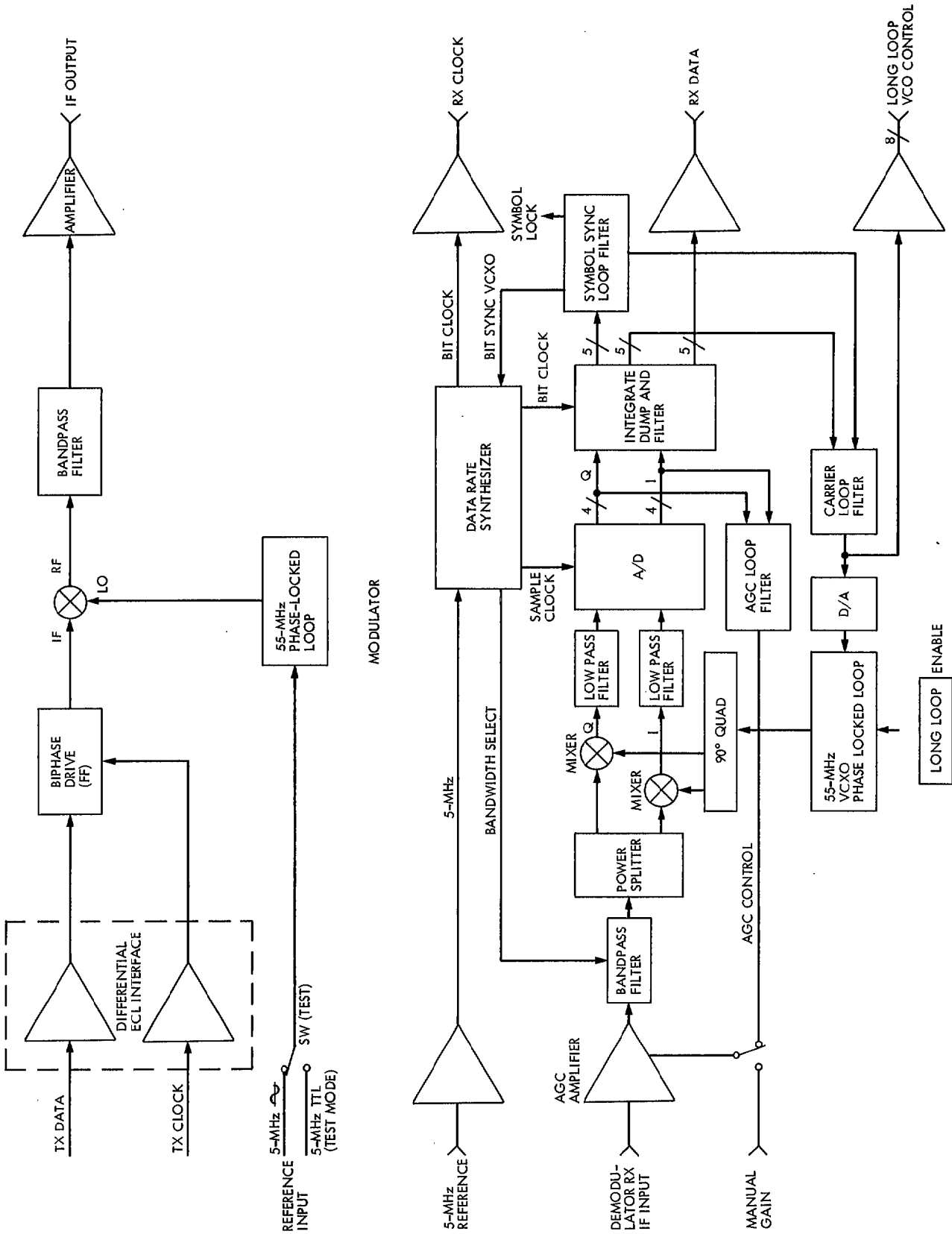


Fig. 1. LM37 MTMD unit block diagram

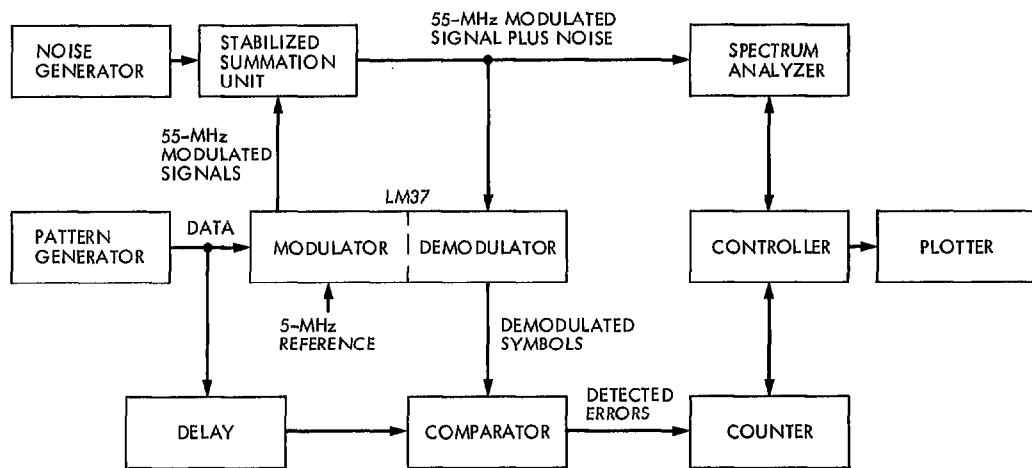
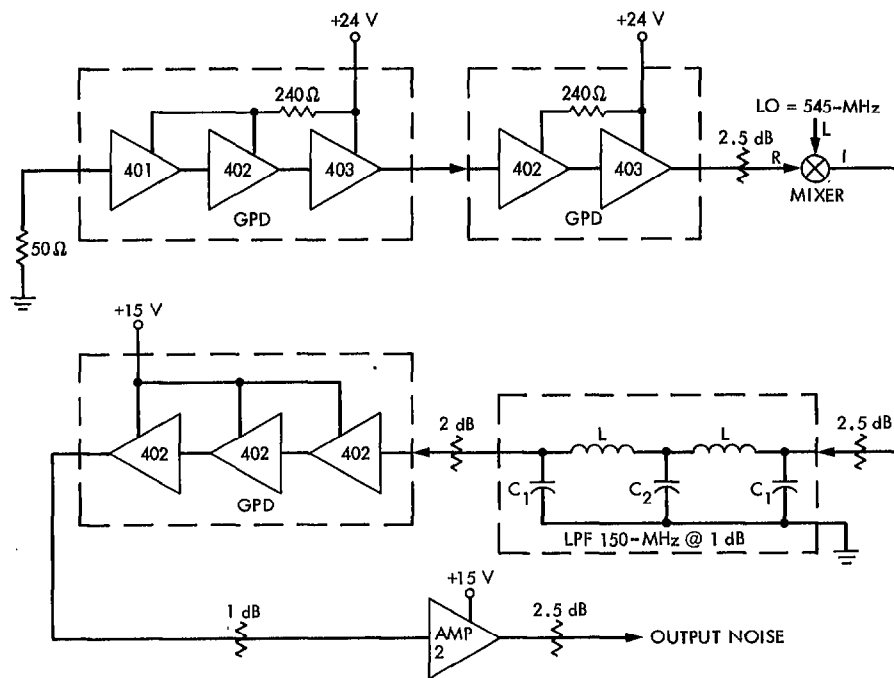


Fig. 2. Symbol error rate test setup



GPD \triangleq MICROCIRCUIT AMPLIFIER
 $L = 0.085 \mu\text{H}$
 $C_1 = 13.1 \text{ pF}$
 $C_2 = 42 \text{ pF}$
 AMP 2 \triangleq AVANTEK UTO 501 AND 502 AMPLIFIER

Fig. 3. Noise generator

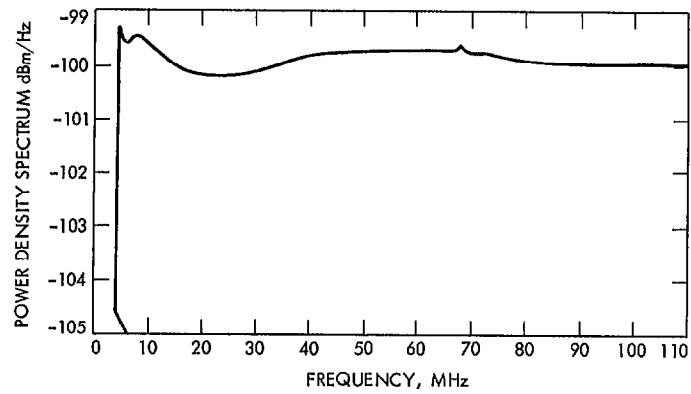


Fig. 4. Generated noise power density spectrum

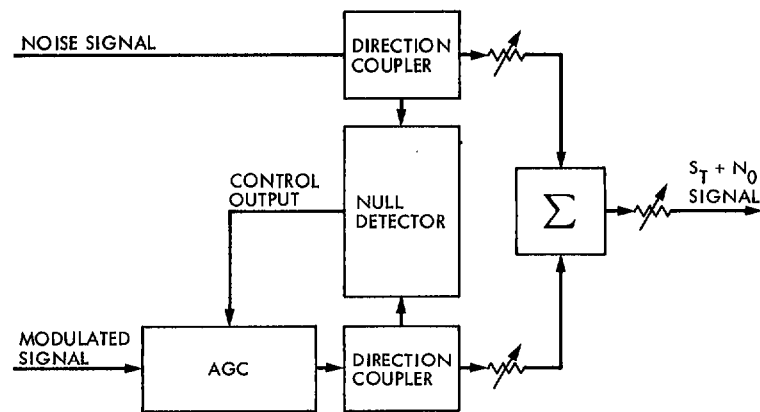


Fig. 5. Stabilized signal and noise summation unit

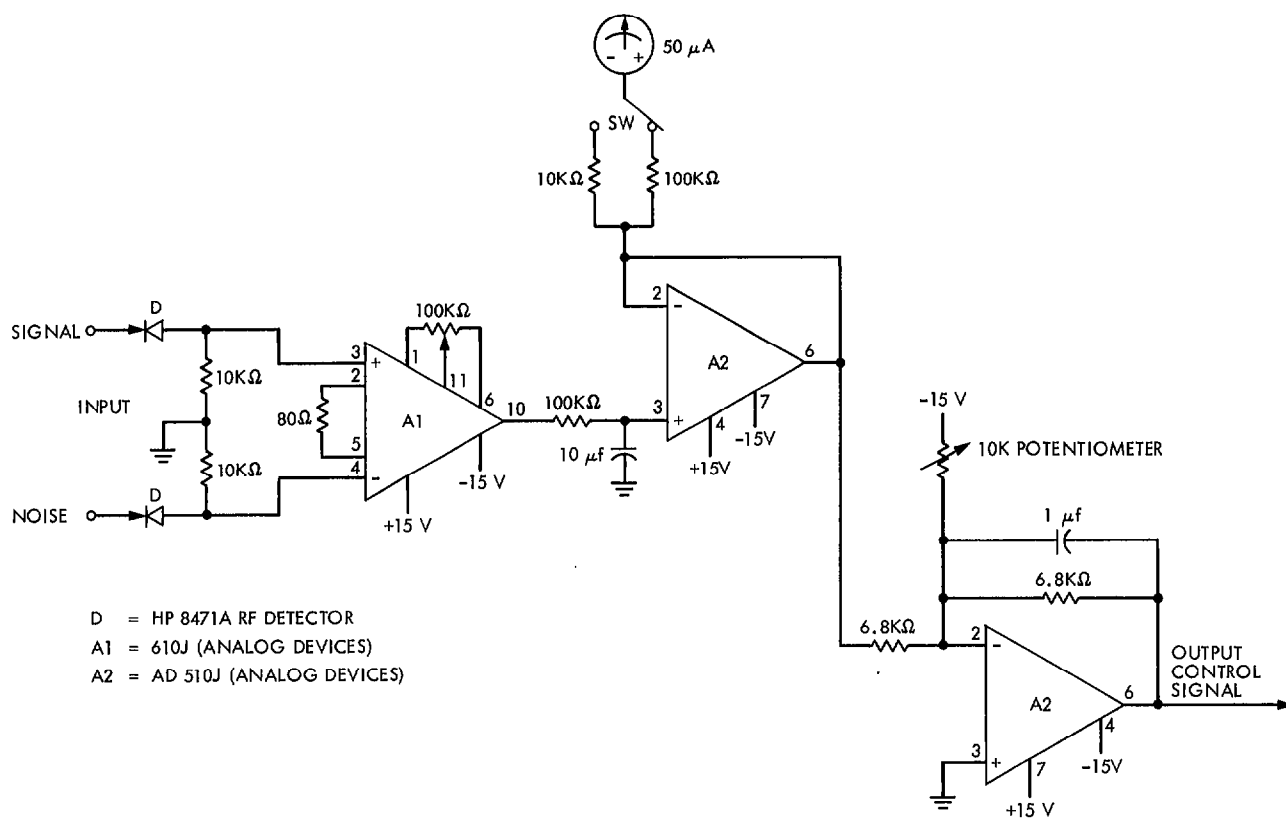
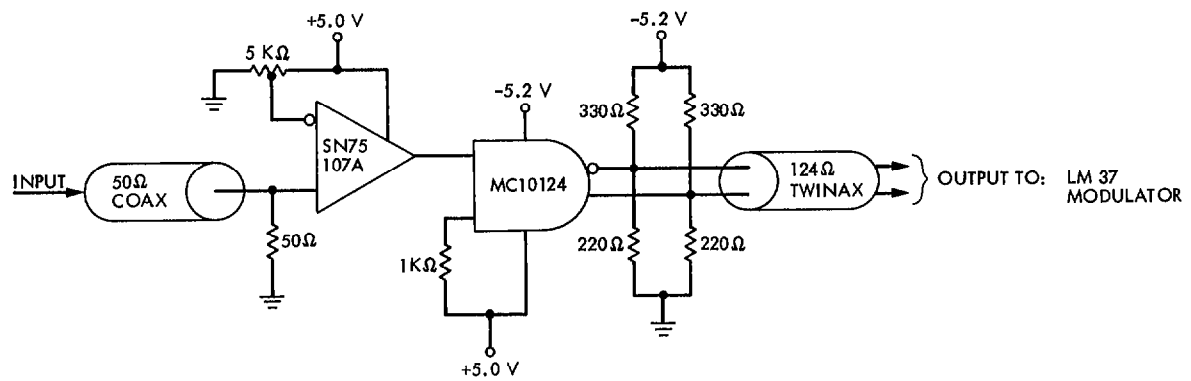
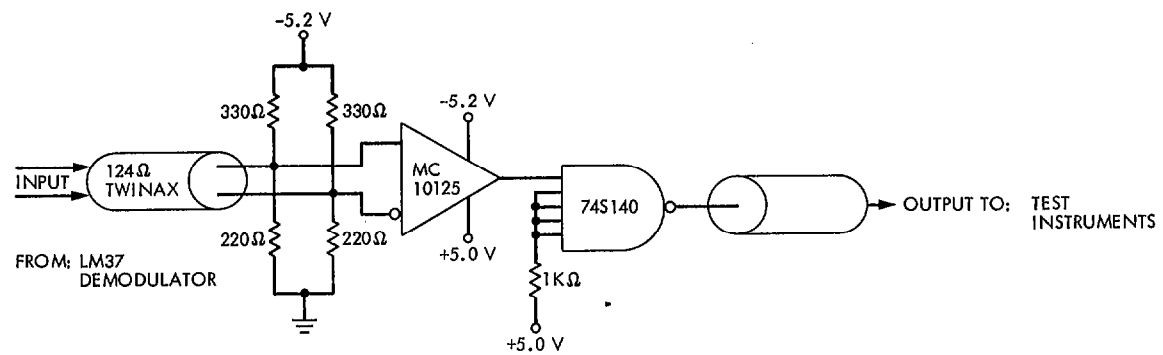


Fig. 6. Null detector



A TYPICAL INPUT SECTION



A TYPICAL OUTPUT SECTION

Fig. 7. Interface unit

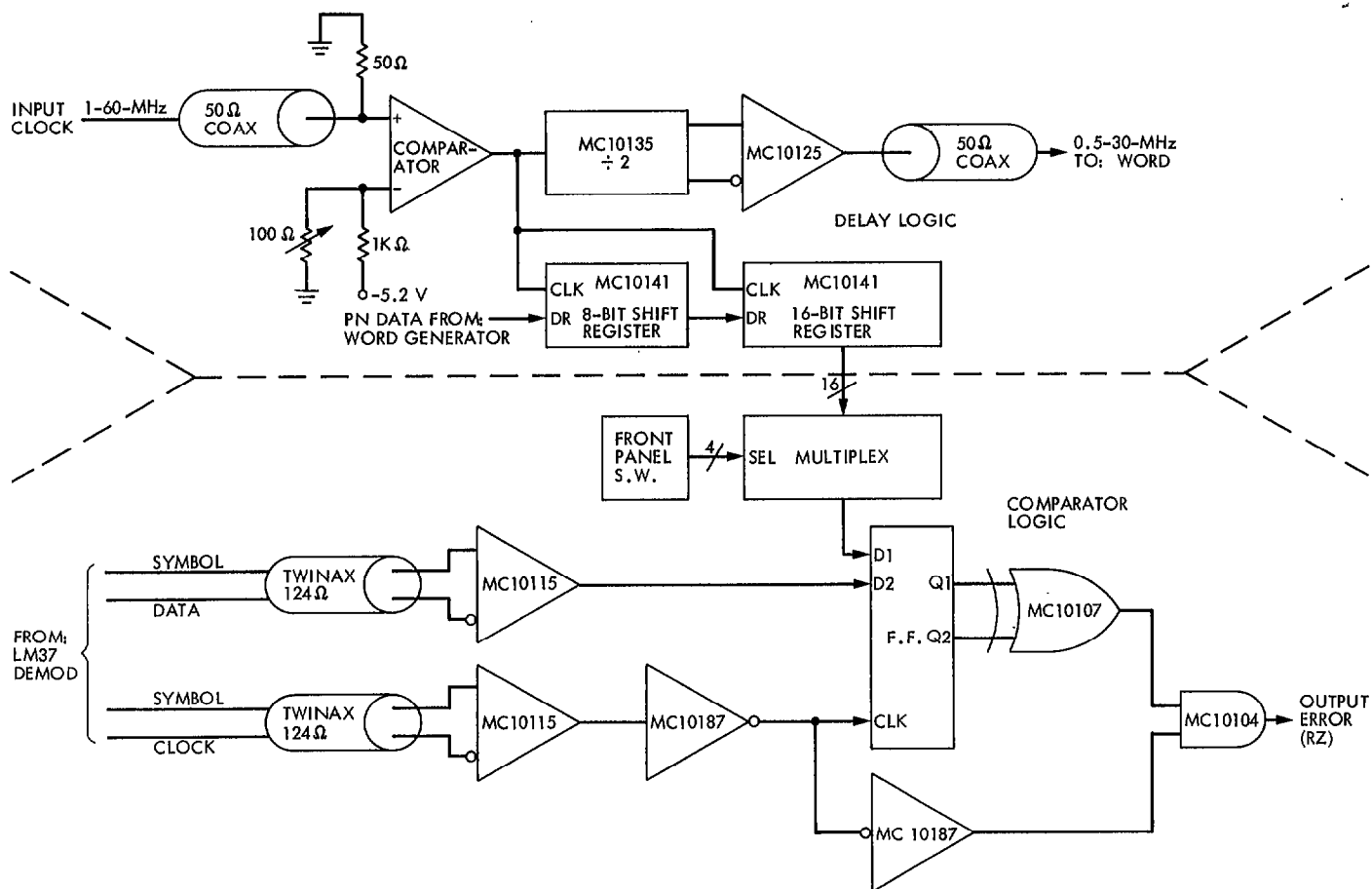


Fig. 8. Delay and error detector unit

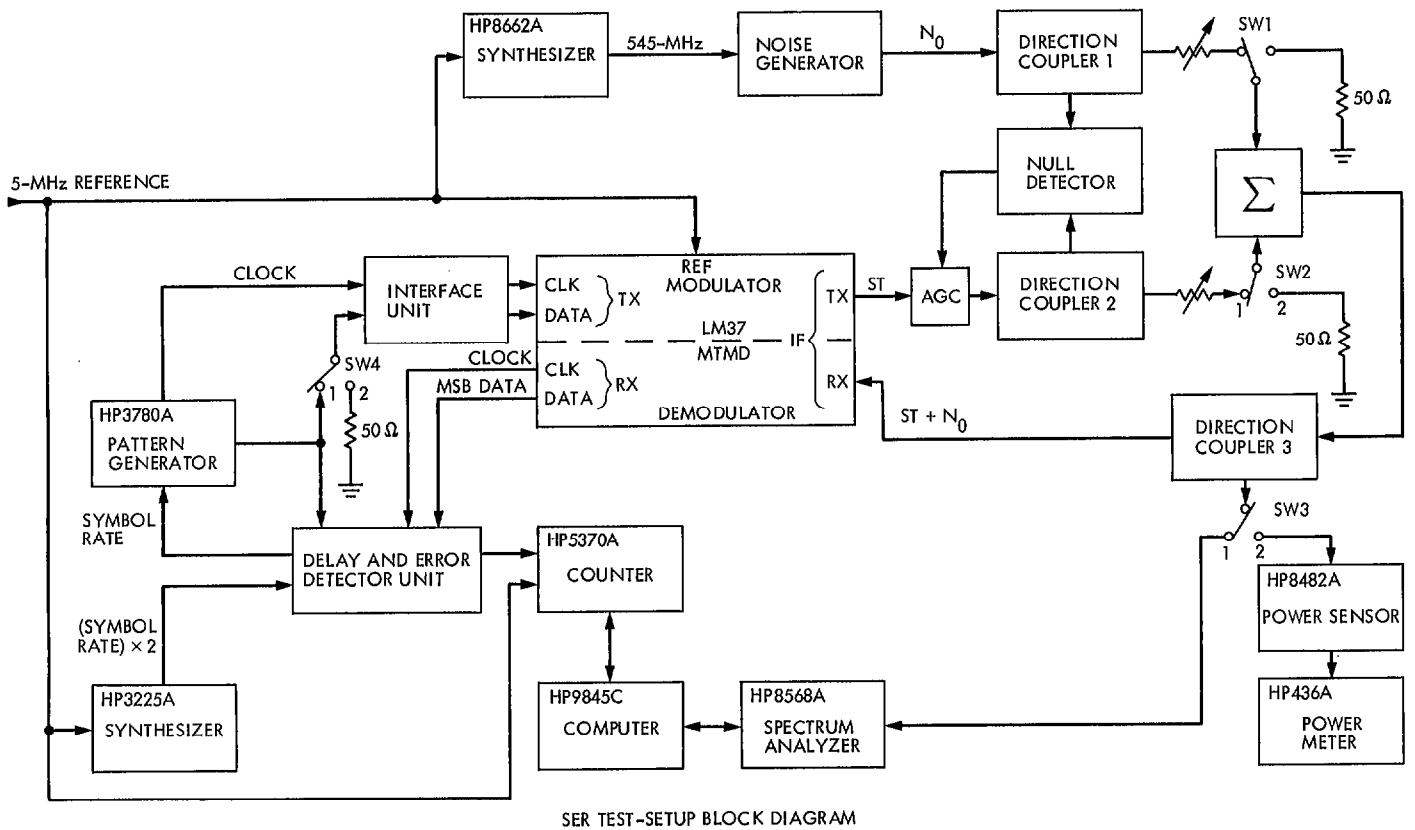


Fig. 9. SER test setup block diagram

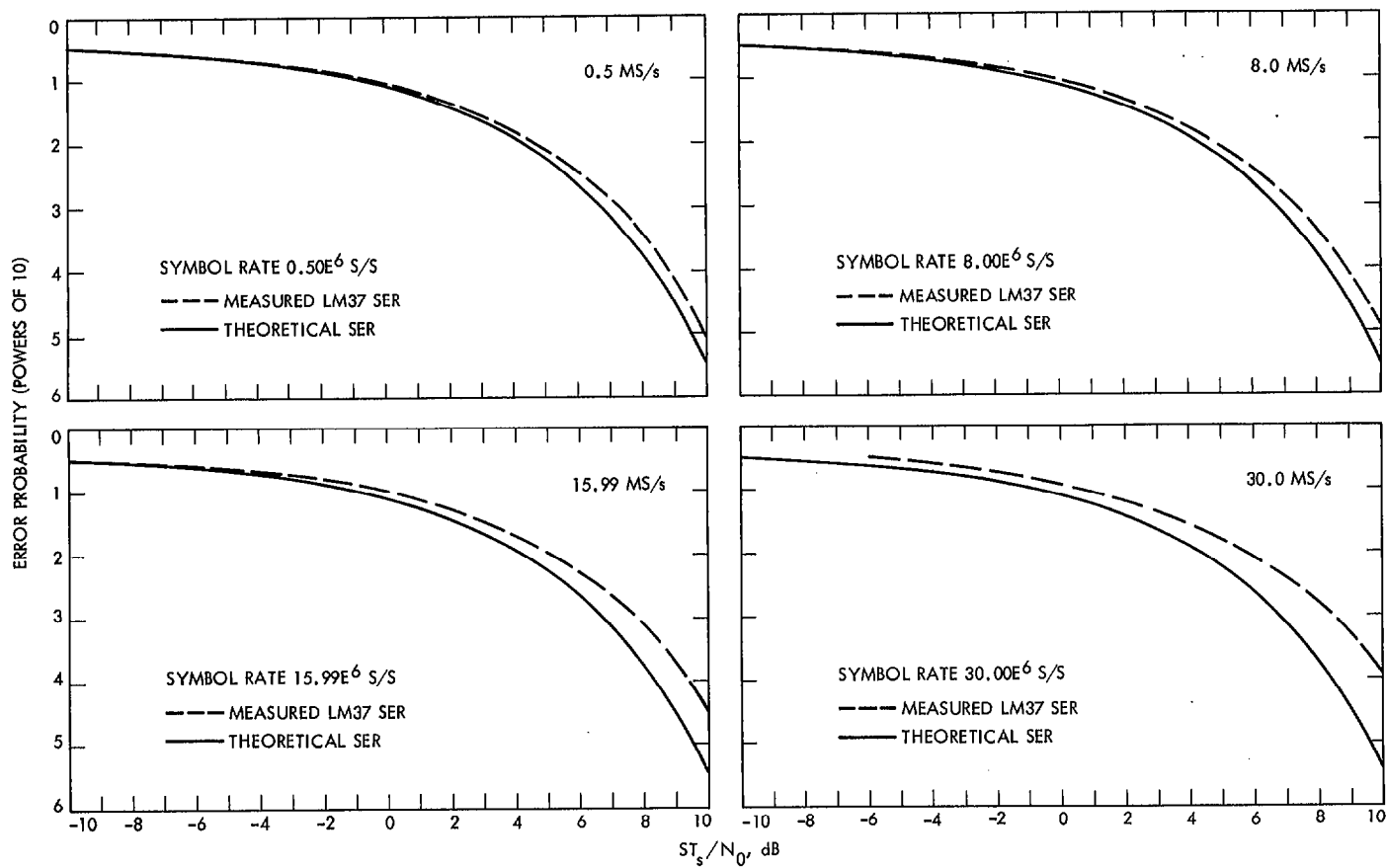


Fig. 10. SER curves

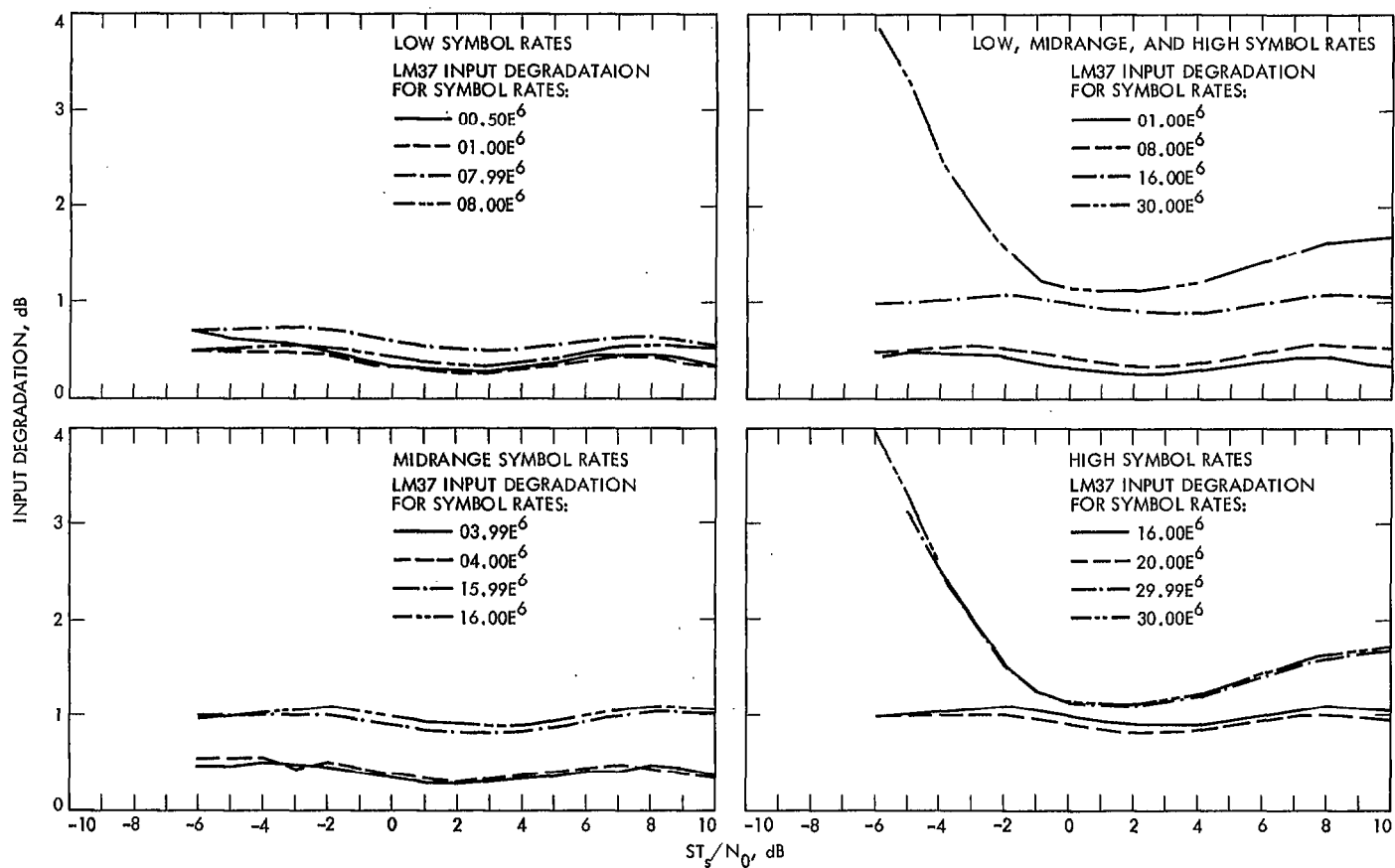


Fig. 11. Input SNR degradation curves